ELSEVIER

Journal of Biomechanics 38 (2005) 755–760

JOURNAL OF BIOMECHANICS

www.elsevier.com/locate/jbiomech
www.JBiomech.com

Effect of abducting and adducting muscle acitivity on glenohumeral translation, scapular kinematics and subacromial space width in vivo

H. Graichen[a,*], S. Hinterwimmer[a,b], R. von Eisenhart-Rothe[a], T. Vogl[c], K.-H. Englmeier[d], F. Eckstein[e]

[a] *Research Group for Kinematics and Biomechanics, Department of Orthopedic Surgery, University of Frankfurt, Marienburgstr. 2, 60528 Frankfurt, Germany*
[b] *Department of Surgery, Klinikum Innenstadt, Ludwig-Maximilians-Universität München, Nußbaumstr. 20, 80336 München, Germany*
[c] *Institute for Medical Informatics, GSF Neuherberg, Ingolstädter Landstr. 1, 85764 Oberschleißheim, Germany*
[d] *Musculoskeletal Research Group, Institute of Anatomy, Ludwig-Maximilians-Universität München, Pettenkoferstr. 11, 80336 München, Germany*
[e] *Institute for Clinical and Interventional Radiology, University of Frankfurt, Theodor Stern Kai 7, 60590 Frankfurt, Germany*

Accepted 12 May 2004

Abstract

It is currently unknown in which ways activity of the ab- and adductor shoulder muscles affects shoulder biomechanics (scapular kinematics and glenohumeral translation), and whether these changes are relevant for alterations of the subacromial space width. The objective of this experimental in vivo study was thus to test the hypotheses that potential changes of the subacromial space width (during antagonistic muscle activity) are caused by alterations of scapular kinematics and/or glenohumeral translation.

The shoulders of 12 healthy subjects were investigated with an open MRI-system at 30°, 60°, 90°, 120° and 150° of arm elevation. A force of 15 N was applied to the distal humerus, once causing isometric contraction of the abductors and once contraction of the adductors. The scapulo-humeral rhythm, scapular tilting and glenohumeral translation were calculated from the MR image data for both abducting and adducting muscle activity.

Adducting muscle activity led to significant increase of the subacromial space width in all arm positions. The scapulo-humeral rhythm (2.2–2.5) and scapular tilting (2–4°) remained relatively constant during elevation, no significant difference was found between abducting and adducting muscle activity. The position of the humerus relative to the glenoid was, however, significantly ($p<0.05$) different (inferior and anterior) for adducting versus abducting muscle activity in midrange elevation (60–120°).

These data show that the subacromial space can be effectively widened by adducting muscle activity, by affecting the position of the humerus relative to the glenoid. This effect may be employed for conservative treatment of the impingement syndrome.

Keywords: Shoulder; MR imaging; Humeral head translation; Scapular kinematics

1. Introduction

A reduction of subacromial space width represents a relevant factor in the pathogenesis of the impingement syndrome (Michener et al., 2003; Neer, 1972). Therefore, the general aim of conservative or surgical therapy has been to enlarge this space (Morrison et al., 1997; Soyer et al., 2003). Several factors have been identified that reduce the width of the space below the acromion, such as acromion morphology (i.e. hooked acromion) (Bigliani et al., 1991), scapular morphology (Anetzberger and Putz, 1996), protraction of the shoulder girdle (Solem-Bertoft et al., 1993), elevation of the arm (Flatow et al., 1994; Graichen et al., 1999a), alteration of the scapulo-humeral rhythm (Graichen et al., 2001; Paletta et al., 1997), and others. These factors have also partly been shown to conincide with the presence of clinical symptoms of impingement syndrome (Bigliani et al., 1991; Flatow et al., 1994; Graichen et al., 2001).

Retraction of the shoulder girdle, in contrast, has been shown to cause a widening of the subacromial

*Corresponding author. Tel.: +49-69-67050; fax: 49-69-6705-375.
E-mail address: h.graichen@em.uni-frankfurt.de (H. Graichen).

0021-9290/$ - see front matter
doi:10.1016/j.jbiomech.2004.05.020

space (Solem-Bertoft et al., 1993). Some of the physiotherapeutic approaches for treating the impingement syndrome are therefore based on the assumption that strengthening of the adductor muscles may be beneficial to enlarge the subacromial joint space (Morrison et al., 1997; Werner et al., 2002). We have previously shown that abducting muscle activity causes a reduction of the subacromial joint space (Graichen et al., 1998, 1999a) and centering of the humeral head relative to the glenoid (Graichen et al., 2000b). It is, however, currently unclear whether such potential alterations of the subacromial space are caused by downward translation of the humeral head, or by alterations of scapular position. Theoretically, an increased tilt of the scapula or a decreased scapulo-humeral rhythm may affect the acromiohumeral distance, albeit the position of the humeral head relative to the glenoid remains constant.

In this study we employ state-of-the-art open MR imaging and 3D postprocessing technology (Graichen et al., 1998, 2000a, b) to address these questions directly in vivo. We test the specific hypotheses that (1) adducting muscle activity causes an increase of scapular tilting and a decrease of the scapulo-humeral rhythm, which indirectly causes an enlargement of the subacromial space, and that (2) adducting muscle activity causes a downward translation of the humeral head relative to the humerus and thus also widens the subacromial space width directly.

2. Material and methods

2.1. Open MR imaging

The shoulders of 12 healthy volunteers (21–33 years) were analyzed. The volunteers had no history of musculo-skeletal disorders, shoulder pain or injury. MR imaging was performed with an open MR system (0.2 T; Magnetom Open; Siemens; Germany) and a T1-weighted 3D gradient recalled echo sequence (TR 16.1, TE 7.0 ms, FA 30°). Image acquisition was performed in an oblique coronal orientation (slice thickness 1.875 mm) perpendicular to the glenoid cavity. The in-plane resolution was 0.86 mm and the acquisition time 4′26 min. The images demonstrated no morphologic alterations in relevant anatomical structures in the 12 volunteers.

The spine of the volunteers was placed precisely in the longitudinal axis of the scanner, this being controlled by a localizer image. To minimize the influence of the supine position on the scapula kinematics the volunteers were positioned on a pad. The pad was adapted individually to each patient (von Eisenhart-Rothe et al., 2002), and permitted free movement of the scapula without interference with the scanner table. The arm was placed in the scapular plane and image acquisition was performed at 5 different elevation angles between 30° and 150°, with neutral rotation of the arm. For reproducible alignment of the shoulder and the arm elevation angle, a special positioning device was used (Graichen et al., 2000a). Beside the elevation angle the rotation angle could also be controlled. Constant isometric muscle activity was achieved by applying first an ADducting force of 15 N, and second an ABducting force of 15 N to the distal humerus. To prevent movement artifacts and to ensure that the humerus was maintained in a constant position during image acquisition, a board was installed on both sides of the positioning device, with which the arm remained in close contact during image acquisition. In a previous study (Graichen et al., 1999b) we have shown with surface electromyographic electrodes that the muscles displayed continuous activity during the 4 min acquisition time at all degrees of abduction (Graichen et al., 1999b). Written consent was obtained of all volunteers and patients prior to MR examination, and all parts of the study had been approved by the local ethics committee.

2.2. Digital image processing and statistical analysis

The image data were transferred to a parallel computing system (Octane Duo, Silicon Graphics Inc., Mountain View, CA). After semi-automated segmentation of the humerus and the scapula (including the articular cartilage of the glenoid and the humeral head) (Haubner et al., 1997), trilinear interpolation and 3D reconstruction was performed as described previously (Englmeier et al., 1994).

For quantitatively characterizing scapular kinematics, the scapulo-humeral rhythm and scapular tilt were calculated. To determine the scapulo-humeral rhythm, we seperated the articular surface of the glenoid cavity from the scapular body, calculated the center of mass of the glenoid cavity in three dimensions, and performed a principal axis decomposition of the inertia tensor of the segmented structures as described previously (Graichen et al., 2000a). Determination of the principal axis of the humerus was performed by the same method. The arm abduction angle (angle between longitudinal axis of the humerus and the spine), the glenohumeral angle (angle between the humerus and the glenoid), and the scapulo-thoracic angle (angle between glenoid and spine) were then calculated (Fig. 1). Finally, the scapulo-humeral rhythm [SHR] (ratio of glenohumeral angle and scapulo-thoracic angle) was analyzed for each arm position according to the method described by Poppen and Walker (1976).

In the frontal plane, the angle between the scapular body and the coronal plane was calculated. This angle is addressed as scapular tilting it describes the amount of "lifting off" of the scapula versus the rib cage. This

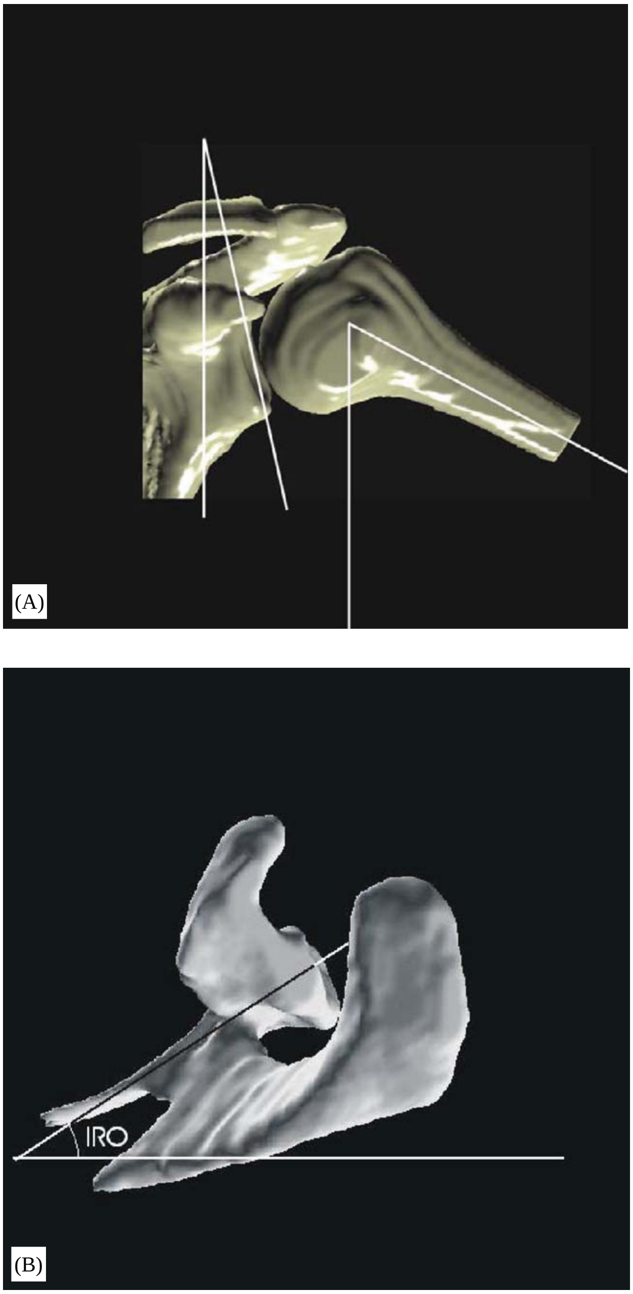

Fig. 1. Characterization of 3D scapular kinematics by (A) determining the scapulo-humeral rhythm and (B) scapular tilting.

angle is used as a measure for retraction and protraction. (Fig. 1).

The glenoid-based coordinate system was used to determine the position of the humeral head and the amount and direction of glenohumeral translation between different arm positions in both the anterior–posterior and superior–inferior direction. (Graichen et al., 2000b; von Eisenhart-Rothe et al., 2000). The data obtained at 30° of abduction were used as reference for quantifying the individual translational movements of the humerus in each patient.

Statistical comparison between adducting and abducting muscle activity in the different elevation angles was performed using a ANOVA post-hoc-test (Bonferroni/Dunn adjustment) setting the maximal accepted error level to $p<0.05$. In view of the multiple tests, significance levels were set to $p<0.0125$ to indicate significance at the 5% global error level, and to $p<0.0025$ to indicate significance at the 1% global error level.

3. Results

3.1. Subacromial space width

In all arm positions, adducting muscle activity led to a significant increase of the minimal acromio–humeral distance compared with abducting muscle activity.

3.2. Scapular kinematics

Under adducting muscle activity, a constant scapulohumeral rhythm of 2.3–2.8 was observed during the entire range of arm elevation (Fig. 2A). During

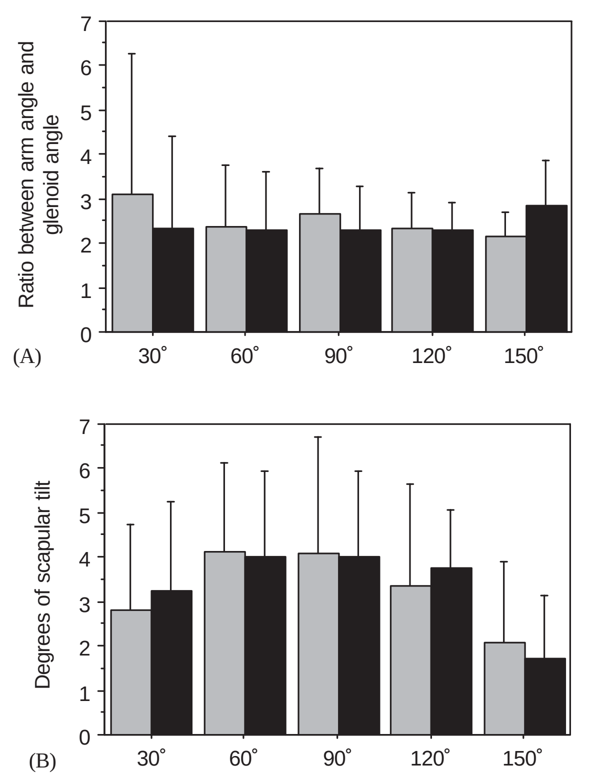

Fig. 2. Mean changes of scapular kinematics and humeral head translation with SD at 30°, 60°, 90°, 120° and 150° of elevation with abduction and adduction muscle activity. Gray bar indicates influence of abducting muscle activity, black bar influence of adducting muscle activity. (A) Scapulo-humeral-rhythm. (B) Scapular tilting. No significant differences were observed between muscle activities in opposite directions.

abducting muscle activity, values ranged from 2.2 to 2.7 between 60° and 150°. Only at 30°, the scapulo-humeral rhythm was somewhat higher (3.1) (Fig. 2A). Statistical comparison showed no significant difference between ab- and adduction muscle activity and between the different elevation angles with regard to the scapulo-humeral rhythm. Constant values for scapular tilting were found (2–4°) under both muscle activites with no significant difference between abducting and adducting muscle activity and between various arm positions (Fig. 2B).

3.3. Glenohumeral translation

During abducting muscle activity, a significant superior translation (0.6–1.8 mm; $p<0.05$) was observed between 30° and 120° of arm elevation in comparison with adducting muscle activity (Fig. 3A). From 120° to 150° of elevation, however, the humeral head translated inferiorly by 0.9 ± 2.1 mm. During adducting muscle activity the position of the humeral head position (relative to the glenoid) was almost constant between 0.2 and 0.3 mm (Fig. 3A). Only at 60° of abduction, the position of the humeral head was 1.00 mm superior to the center of the glenoid. Comparing ab- and adducting muscle activity displayed a significantly more inferior position of the humeral head between 90° and 120° ($p<0.05$) (Fig. 3A).

In anterior/posterior direction, the humeral head was positioned posterior to the center of the glenoid (1.3–2.3 mm) at all elevation angles under abducting muscle activity (Fig. 3B). There was no significant difference in humeral head postion between various arm positions. Under adducting muscle activity, the head was positioned anteriorly, with values of 0.2–1.4 mm at lower elevation angles. At 120° of elevation, the humeral head was almost centered while at 150° it was positioned posteriorly (0.9 mm) under adducting muscle force (Fig. 3B). Between 90° and 150° of elevation, a significant posterior translation of the humeral head was observed relative to abducting muscle activity. Comparing ab- and adducting muscle activity displayed a significant anterior (60°, 90° and 120°; $p<0.0025$) position of the humeral head under the influence of adducting muscle activity (Fig. 3B).

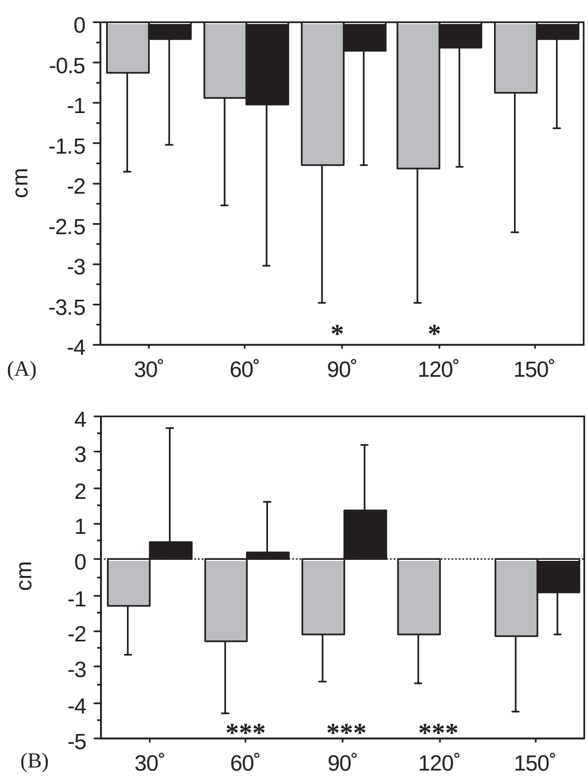

Fig. 3. (A) Superior/inferior movement of the humeral head relative to the center of the glenoid. Negative values indicate superior movement of the humeral head. Humeral head shows significant inferior position through adduction muscle activity in 90° and 120° of elevation. $^{*}p<0.05$ in single test; $^{**}p<0.05$ at global level [<0.0125 in single test]; $^{***}p<0.01$ at global level [<0.0025 in single test]; (B) Anterior/posterior movement of the humeral head relative to the center of the glenoid. Negative values indicate posterior movement of the humeral head. Humeral head shows significant anterior position under the influence of adducting muscle activity at 60°, 90° and 120° of elevation. $^{*}p<0.05$ in single test; $^{**}p<0.05$ at global level [<0.0125 in single test]; $^{***}p<0.01$ at global level [<0.0025 in single test].

4. Discussion

In this study we have analyzed the effect of adducting and abducting muscle activity on the subacromial space width during elevation of the arm. Moreover, the study was designed to clarify whether potential changes in subacromial space width are caused by alterations of scapular kinematics and/or humeral head position. We hypothesized that both scapular kinematics and gleno-humeral head position were associated with subacromial joint space width. Whereas the position of the humeral head relative to the glenoid directly determines the width between the humeral head and acromion, the rotation and tilt of the scapula determines the specific position of the acromion and may thus affect the acromiohumeral distance, independent of the humeral head position relative to the glenoid. Since the thoracoscapular muscles determine the position of the scapula, it is conceivable that different muscle activites (ab- and adductor contraction) alter the position of the scapula and thus have an indirect effect on the width of the subacromial joint space.

By applying state-of-the-art 3D MR imaging and postprocessing technology we were able to demonstrate, that adducting muscle activity widens the subacromial space width relative to abducting muscle activity. Contrary to our hypothesis, however, only the inferior and anterior translation of the humeral head versus the glenoid during adductor muscle activity was responsible for this increase, whilst scapular kinematics was not different between ab- and adducting muscle activity.

The minimal distance between the humeral head and the acromion represents an established quantitative parameter of subacromial joint space width. Studies with conventional radiography have shown that values of >6 mm are normal under physiological conditions (Golding, 1962; Petersson and Redlund-Johnell, 1984; Weiner and Macnab, 1970). The limitation of radiography, however, is its projectional nature. Potential artefacts result from the superpositioning of various anatomical structures onto a two-dimensional film. Recent studies with open MR imaging techniques have demonstrated that the acromiohumeral distance is dependent on the arm elevation angle. A decrease of 2–3 mm has been observed from 30 to 90° of elevation (Graichen et al., 1999a). This corresponds with the clinical finding that in patients with impingement syndrome the pain is most pronounced between 60° and 120° of elevation. Flatow et al. (1994) have shown under in vitro conditions that narrowing between the humeral head and the acromion occurs in these positions.

Abducting muscle activity has been identified to reduce subacromial space width in vitro and in vivo (Graichen et al., 1998, 1999a; Perry, 1988; Wuelker et al., 1995). However, it has remained unclear whether changes of the subacromial space width are primarily caused by humeral head translation or/and by alterations of the scapular kinematics. The limitations of radiographic studies (Paletta et al., 1997; Poppen and Walker, 1976) in characterizing glenohumeral translation and scapular kinematics were overcome by using a three-dimensional imaging and postprocessing technique (Graichen et al., 1998). This technology allowed us to determine all spatial parameters (subacromial space width, glenohumeral position, scapular kinematics) simultaneously.

A limitation of the open MRI technique is the relatively long acquisition time. A minimal imaging time of 2–5 min is required for acquiring 3D data sets with complete anatomical coverage of all relevant structures. It must be considered that the results of this quasi static assessment of the joint might differ from those obtained under dynamic circumstances. For performing dynamic studies, single 2D images can be obtained at time intervals of around 1 s. However, as for radiography single 2D images suffer from limited reproducibility and do not permit to adequately address the questions examined in our current study.

Here we show that the increase of the subacromial space width during adducting muscle activity is caused by inferior and also by anterior translation of the humeral head relative to the glenoid. This confirms that a 3D analysis is required to capture glenohumeral joint biomechanics during normal neuromuscular activity. A significant inferior and anterior translation was found for adducting muscle activity and all arm positions, except for 30° of elevation.

While alterations of scapula kinematics are often observed for various clinical pathologies of the shoulder (Graichen et al., 2001; Ozaki, 1989; Warner et al., 1992), we found no differences of scapular rotation and tilt between adducting and abducting muscle activity under physiologic conditions. Moreover, the standard deviation between the individuals was very small, suggesting that scapular kinematics in healthy shoulders is very constant and displays little intersubject variability. This applied to both the scapulo-humeral rhythm as well as to scapula tilting.

In conclusion we show here, for the first time in vivo, that the physiological increase of subacromial space width under adducting muscle activity at various elevation angles is caused by inferior and anterior translation of the humeral head relative to the glenoid. Scapular kinematics, in contrast, was not altered by muscle forces in opposite directions. These relationships indicate that it may indeed be possible to treat patients with impingement syndrome conservatively, by strengthening the adductor muscles.

Acknowledgements

We would like to express our thanks to the Deutsche Forschungsgemeinschaft (DFG; GR 1638/5-1, 5-2) and the Klein foundation for support.

References

Anetzberger, H., Putz, R., 1996. The scapula: principles of construction and stress. Acta Anatomica 156, 70–80.

Bigliani, L.U., Ticker, J.B., Flatow, E.L., Soslowsky, L.J., Mow, V.C., 1991. The relationship of acromial architecture to rotator cuff disease. Clinics in Sports Medicine 10, 823–838.

Englmeier, K.-H., Haubner, M., Fink, U., Fink, B., 1994. Image analysis and synthesis of multimodal images in medicine. Computer Methods and Programs in Biomedicine 43, 193–206.

Flatow, E.L., Soslowsky, L.J., Ticker, J.B., Pawluk, R.J., Hepler, M., Ark, J., Mow, V.C., Bigliani, L.U., 1994. Excursion of the rotator cuff under the acromion. Patterns of subacromial contact. American Journal Sports and Medicine 22, 779–788.

Golding, F.C., 1962. The shoulder: the forgotten joint. British Journal of Radiology 35, 149–158.

Graichen, H., Bonel, H., Stammberger, T., Heuck, A., Englmeier, K.-H., Reiser, M., Eckstein, F., 1998. A technique for determining the spatial relationship between the rotator cuff and the subacromial space in arm abduction using MRI and 3D image processing. Magnetic Resonance in Medicine 40, 640–643.

Graichen, H., Bonel, H., Stammberger, T., Haubner, M., Englmeier, K.-H., Reiser, M., Eckstein, F., 1999a. Subacromial space width changes during abduction and rotation–a 3-D MR imaging study. Surgical Radiologic and Anatomy 21, 59–64.

Graichen, H., Bonel, H., Stammberger, T., Haubner, M., Rohrer, H., Englmeier, K.-H., Reiser, M., Eckstein, F., 1999b. Three-dimensional analysis of the width of the subacromial space in healthy subjects and patients with impingement syndrome. American Journal of Roentgenology 172, 1081–1086.

Graichen, H., Stammberger, T., Bonel, H., Haubner, M., Englmeier, K.-H., Reiser, M., Eckstein, F., 2000a. Magnetic resonance-based motion analysis of the shoulder during elevation. Clinical Orthopedics 370, 154–163.

Graichen, H., Stammberger, T., Bonel, H., Englmeier, K.-H., Reiser, M., Eckstein, F., 2000b. Glenohumeral translation during active and passive elevation of the shoulder—a 3D open-MRI study. Journal of Biomechanics 33, 609–613.

Graichen, H., Stammberger, T., Bonel, H., Wiedemann, E., Englmeier, K.-H., Reiser, M., Eckstein, F., 2001. Three-dimensional analysis of shoulder girdle and supraspinatus motion patterns in patients with impingement syndrome. Journal of Orthopaedic Research 19, 1192–1198.

Haubner, M., Krapichler, C., Loesch, A., Englmeier, K.-H., vanEimeren, W., 1997. Virtual Reality in medicine—computer graphics and interaction techniques. IEEE Transaction on Information Technology in Biomedicine. 1 61-72.

Michener, L.A., McClure, P.W., Karduna, A.R., 2003. Anatomical and biomechanical mechanisms of subacromial impingement syndrome. Clinical Biomechanics 18, 369–379.

Morrison, D.S., Frogameni, A.D., Woodworth, P., 1997. Non-operative treatment of subacromial impingement syndrome. Journal of Bone and Joint Surgery American Volume 79, 732–737.

Neer II, C.S., 1972. Anterior acromioplasty for the chronic impingement syndrome in the shoulder: A preliminary report. Journal of Bone and Joint Surgery 54, 41–50.

Ozaki, J., 1989. Glenohumeral movements of the involuntary inferior and multidirectional instability. Clinical Orthopaedics 238, 107–111.

Paletta., Jr, G.A., Warner, J.J., Warren, R.F., Deutsch, A., Altchek, D.W., 1997. Shoulder kinematics with two-plane X-ray evaluation in patients with anterior instability or rotator cuff tearing. Journal of Shoulder and Elbow Surgery 6, 516–527.

Perry, J., 1988. Biomechanics of the shoulder. In: Rowe, C.R. (Ed.), The Shoulder. Churchill Livingston, New York, pp. 1–15.

Petersson, C.J., Redlund-Johnell, I., 1984. The subacromial space in normal shoulder radiographs. Acta Orthopaedica Scandinavica 55, 57–58.

Poppen, N.K., Walker, P.S., 1976. Normal and abnormal motion of the shoulder. Journal of Bone and Joint Surgery American Volume 58, 195–201.

Solem-Bertoft, E., Thuomas, K.A., Westerberg, C.E., 1993. The influence of scapular retraction and protraction on the width of the subacromial space. An MRI study. Clinical Orthopaedics 296, 99–103.

Soyer, J., Vaz, S., Pries, P., Clarac, J.P., 2003. The relationship between clinical outcomes and the amount of arthroscopic acromial resection. Arthroscopy 19, 34–39.

von Eisenhart-Rothe, R., Wiedemann, E., Bonel, H., Eckstein, F., Reiser, M., Englmeier, K.-H., Graichen, H., 2000. MRI-based 3-D analysis of the glenohumeral translation in patients with shoulder instability. Zetschrift Orthopadic Ihrefur Grenzgebiete 138, 481–486.

von Eisenhart-Rothe, R.M., Jager, A., Englmeier, K.-H., Vogl, T.J., Graichen, H., 2002. Relevance of arm position and muscle activity on three-dimensional glenohumeral translation in patients with traumatic and atraumatic shoulder instability. American Journal of Sports Medicine 30, 514–522.

Warner, J.J., Micheli, L.J., Arslanian, L.E., Kennedy, J., Kennedy, R., 1992. Scapulothoracic motion in normal shoulders and shoulders with glenohumeral instability and impingement syndrome. A study using Moire topographic analysis. Clinical Orthopaedics 285, 191–199.

Werner, A., Walther, M., Ilg, A., Stahlschmidt, T., Gohlke, F., 2002. Self-training versus conventional physiotherapy in subacromial impingement syndrome. Zetscriftfur Orthopadic 140, 375–380.

Weiner, D.S., Macnab, I., 1970. Superior migration of the humeral head. A radiological aid in the diagnosis of tears of the rotator cuff. Journal of Bone and Joint Surgery Bristish Volume 52, 524–527.

Wuelker, N., Wirth, C.J., Plitz, W., Roetman, B., 1995. A dynamic shoulder model: reliability testing and muscle force study. Journal of Biomechanics 28, 489–499.